$BVRI$ Light Curves for 29 Type Ia Supernovae

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ABSTRACT

$BV(RI)_{KC}$ light curves are presented for 27 Type Ia supernovae discovered during the course of the Calán/Tololo Survey and for two other SNe Ia observed during the same period. Estimates of the maximum light magnitudes in the B, V, and I bands and the initial decline rate parameter $\Delta\mathrm{m}_{15}(B)$ are also given.

Subject headings: photometry — supernovae

1. Introduction

The Calán/Tololo Supernova Survey was begun in 1990 as a collaboration between astronomers at Cerro Tololo Inter-American Observatory (CTIO) and the Cerro Calán Observatory of the University of Chile with the principal goal of examining the Hubble diagram for type Ia supernovae (SNe Ia) out to redshifts of ∼0.1. During the course of the survey, which we completed in November 1993, a total of 32 SNe Ia were discovered and spectroscopically confirmed. Of these, useful follow-up CCD photometry was obtained for 27 events. In addition, as part of the same program, light curves were obtained of 2 SNe Ia discovered at other observatories.

In this paper, we present the final reduced $BVRI$ light curves for these 29 SNe Ia, along with estimates of the maximum-light magnitudes in BVI and the initial decline rate parameter $\Delta m_{15}(B)$ (Phillips 1993). Note that preliminary light curves for a few events have appeared in previous publications (Hamuy et al. 1993a, hereafter referred to as Paper I; Maza et al. 1994, hereafter referred to as Paper II; Hamuy et al. 1994, hereafter referred to as Paper III). In two accompanying papers, we use these data to examine 1) the absolute luminosities of the sample (Hamuy et al. 1996a, hereafter referred to as Paper V) and 2) the Hubble diagrams in BVI and value of the Hubble constant (Hamuy et al. 1996b hereafter referred to as Paper VI).

2. Observations

The search phase of the Calán/Tololo Supernova Survey consisted of photographic observations of 45 fields taken with the Curtis Schmidt Camera, with observations carried out approximately twice a month over the 1990-93 period. The details of these observations were described in considerable detail in Paper I, and therefore will not be repeated here.

The follow-up phase consisted of two parts: 1) classification via optical spectroscopy, and 2) photometric monitoring via direct CCD imaging in the $BV(RI)_{KC}$ system. Of the 50 SNe discovered in the course of the Survey for which classification spectra were obtained, 32 (64%) were found to be type Ia events. A complete listing of these SNe Ia is found in Table 1 which gives: the SN and host galaxy names, the morphology and heliocentric redshift of the host galaxy; the line-of-sight extinction due to our own Galaxy (Burstein & Heiles 1982); the SN equatorial coordinates derived from an early-epoch CCD image using reference stars measured from the digitized sky survey plates available from the Space Telescope Science Institute; the offset of the SN from the host galaxy nucleus; the estimated photographic magnitude of the SN on the discovery plate; the name of the discoverer; and the UT discovery date. A V band CCD image of each SN is reproduced in Figure 1.

Followup photometry was obtained for as many of these events as proved practical. Spectra of three of the SNe (1992O, 1992ai, and 1993af) showed that these had been caught several weeks or months past maximum light; hence, the decision was made not to concentrate on obtaining follow-up photometry of these events. For two of the more distant SNe, 1993M and 1993T, an insufficient number of observations were secured to provide adequate coverage of the light curves. Hence, the final number of Calán/Tololo SNe Ia for which light curves were ultimately obtained was 27.

In addition to these 27 SNe, we obtained $BVRI$ photometry of two other SNe Ia, 1990O and 1992al, which were discovered at other observatories during the course of the survey. Information for these two events is included at the end of Table 1, and V band CCD images are shown in Figure 2. Thus, in this paper we present light curves for a total of 29 SNe Ia.

The follow-up photometry for all 29 SNe Ia was obtained with CCD detectors on a total of 302 nights between 1990 July 4 and 1995 February 11 thanks to the extensive

collaboration of many visiting astronomers and CTIO staff members. The vast majority (94%) of these nights were at CTIO, with the remaining observations being carried out with the Las Campanas Observatory (LCO) 1.0-m telescope and four different telescopes at the European Southern Observatory (ESO). At CTIO, fully 90% of the data were taken with the 0.9-m telescope, with the remainder coming from the 1.5-m and 4.0-m telescopes[1]. A complete journal of the observations is given in Table 2, which contains the following information: the UT date, the telescope employed, the observatory, the identity of the CCD detector, and the observer(s).

3. Photometric Reductions

A detailed description of the procedures we followed to produce $BVRI$ magnitudes from the individual CCD images of each SN has been given in Paper III. The various steps are summarized as follows:

1. Several deep CCD images (in each color) were obtained of the SN field after the SN had faded from detection. These images were transformed geometrically to the same scale, and then coadded to produce a deep master image of the host galaxy.

2. The master galaxy image was transformed and scaled to the flux scale of each individual SN image, and then subtracted. In order to save computing time, this galaxy subtraction was carried out over only a subset of the image centered on the SN (see Figure 2 of Paper III).

[1]This project serves as an eloquent illustration of the capabilities of "small" telescopes equipped with state-of-the-art CCD detectors.

3. Instrumental magnitudes of the SN and several field local standard stars were then measured from the galaxy-subtracted images via point spread function fitting.

4. Finally, the instrumental magnitudes were transformed to the standard $BV(RI)_{KC}$ system through the use of a photometric sequence set up in the same field surrounding the SN. (See Paper I for further details of the exact photometric transformations employed.) The photometric sequences for all 29 SNe are identified in the finder charts in Figures 1 and 2. Only three stars lie outside the observed fields and could not be identified in these charts, namely: c8 in the field of SN 1990Y which is located about 130 arcsec west from star c6; c10 in the field of SN 1990Y which is located about 160 arcsec west and 35 arcsec south from star c6; and c14 in the field of SN 1990af which is located about 10 arcsec south and 40 arcsec east from star c12. The magnitudes for the photometric sequences are listed in Table 3. In every case, these sequences were derived from observations made on several (typically 4-6) photometric nights. The uncertainties quoted correspond to the standard error of the mean.

Table 4 lists the final reduced photometry for each SN. Please note that these magnitudes supersede all previously published values (papers I, II, and III) for the same SNe. The uncertainties quoted for each magnitude correspond to the sum in quadrature of the errors due to photon Poisson statistics and an *assumed* additional error of 0.03^m in each individual observation. The latter uncertainty was included in order to account for errors involved in the transformation from our instrumental system to the standard system, and also due to the subtraction of the underlying host galaxy.

4. Maximum-Light Magnitudes & Decline Rates

Figure 3 shows the BVI light curves of the 29 SNe Ia included in this study. Maximum-light magnitudes were derived for each SN in one of the following two methods:

1. *Direct Measurement.* For 11 SNe (slightly more than one third of the sample), photometry was obtained at or before maximum light allowing direct measurement of the maximum-light magnitudes in B and V. However, for several of these objects (e.g., see the light curves of SN 1992ag in Figure 3), coverage of the I light curve was insufficient to allow direct measurement of the maximum-light brightness in this band. In these cases, the best fitting template (see below) was used, often adjusting this to the first I data point. The corresponding error in the peak magnitude was taken to be 0.03^m in those cases where the coverage of the light curve started before maximum, and 0.05^m when the observations started only one or two days before the peak.

2. *Template Fitting.* For the majority of the SNe in our sample, the light curve observations did not begin until after maximum light. To estimate peak magnitudes for these events, we employed a template fitting procedure similar to that utilized in Paper III and Hamuy et al. 1995 (hereafter referred to as Paper IV). As detailed in a separate paper (Hamuy et al. 1996c; hereafter referred to as Paper VIII), a family of six BVI light curve templates, representing the range of observed decline rates of SNe Ia, were produced from precise CCD photometry obtained at CTIO of seven well-observed events (1992bc, 1991T, 1992al, 1992A, 1992bo, 1993H, and 1991bg). These templates were fit to the observed photometry of each of the program SNe via a χ^2-minimizing technique which solved simultaneously for the time of B maximum and the peak magnitudes B_{MAX}, V_{MAX}, and I_{MAX}. (Note that in our previous papers, the I-band data was not included.) As detailed in Paper III, before performing these fits,

the templates were first modified by the appropriate K terms (Hamuy et al. 1993b) and were also stretched to account for time dilation. For about half of the SNe, one of the templates provided a much better fit (as judged by the value of the reduced χ^2) than the others. An example is SN 1992ae (see Figure 3) whose BVI light curves were found to be an excellent match to the SN 1992al templates. However, for many of the program SNe, the data were fit essentially equally well by two different templates. A good example of such an event is SN 1991ag (see Figure 3), for which the 1991T and 1992bc templates yielded similar values of the reduced χ^2. Hence, we adopted the general rule that when the difference in the reduced χ^2 of two template fits was $\leq$1.5, the peak magnitudes were obtained by averaging the results for the two templates. The corresponding errors were taken to be the greater of a) half of the difference between the peak magnitude estimates of the two templates, b) the 2σ formal errors of the χ^2 fits, or c) 0.05^m. When the difference in the reduced χ^2 values was $>$1.5, the maximum-light magnitudes were taken from the single-best fitting template, with the adopted error being the larger of the 2σ formal error of the χ^2 fit or 0.05^m. Although these rules produced reasonable error estimates in most cases, we found that the errors derived for some SNe whose first light curve observations did not begin until $\sim$2 weeks after maximum were unrealistically low. Hence, in all cases where template fits indicated that the first photometry was not obtained until $\geq$10 days after B maximum, we adopted the following error estimates: 0.2^m in B, 0.15^m in V, and 0.15^m in I.

For each of the 29 SNe in our sample, we also estimated the decline rate parameter $\Delta m_{15}(B)$ (Phillips 1993) which corresponds to the amount in magnitudes that the B light curve decreases in brightness during the first 15 days after maximum . This parameter could be measured directly for the five best-observed SNe in the sample (1990af, 1992al, 1992bc, 1992bo, and 1993O). For the remaining events, $\Delta m_{15}(B)$ was estimated by fitting

a parabola to the reduced χ^2 values yielded by the six template fits (see Paper IV for further details of this procedure). Note that when the smallest value of the reduced χ^2 corresponded to either of the two extremes of the range of $\Delta m_{15}(B)$ represented by our templates (SN 1992bc with $\Delta m_{15}(B) = 0.87$ and SN 1991bg with $\Delta m_{15}(B) = 1.93$), we set the inferred value of $\Delta m_{15}(B)$ to the same value as the template rather than attempting to extrapolate a value.

Table 5 summarizes the resulting light curve parameters for all 29 SNe Ia. Specifically, we give the epoch of B maximum; the time with respect to B_{MAX} of the first photometric observation in B, V, or I; the decline rate parameter $\Delta m_{15}(B)$; the apparent maximum-light magnitudes in B, V, and I; and the method employed to estimate the peak magnitudes where *Data* means that the values were measured directly from the photometry, *Single Fit* indicates that the best fitting template was used, and *Average* signifies that the results from the two best template fits were averaged. In Figure 4 we plot a histogram of the time with respect to B_{MAX} of the first photometric observation in B, V, or I for the 29 Calán/Tololo SNe Ia.

In Table 6, we repeat the $\Delta m_{15}(B)$ values and give our final estimates of the peak magnitudes after correction for the extinction due to our own Galaxy (see Table 1) and the K term. The uncertainties in the corrected magnitudes include errors in the observed magnitude (listed in Table 5), foreground reddening (0.06^m in B, 0.045^m in V, and 0.03^m in I), as well as in the K term (assumed to be $\pm 0.02^m$). We also list the "color" of the SN, $B_{MAX} - V_{MAX}$. (Note that, strictly speaking, this is not a color since B_{MAX} and V_{MAX} occur at slightly different times.) The uncertainties in the color were estimated in the following manner: a) for the 11 SNe for which the photometry started before maximum light we adopted an error of 0.03^m when the peak was very well observed (6 cases), or 0.05^m otherwise (5 cases), b) when the coverage of the light curve started between days 1 and 10

(counted since B_{MAX}) the adopted error was the larger of half of the difference between the color estimates of the two templates or 0.05^m; if the single-best fitting template technique was used we adopted an error of 0.05^m, or c) when the observations started after day 10 (counted since B_{MAX}) the adopted error was the larger of half of the difference between the color estimates of the two templates or 0.10^m; if the single-best fitting template technique was used we adopted an error of 0.10^m.

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Figure Captions

Fig. 1.— V band CCD images of the 32 SNe Ia discovered in the course of the Calán/Tololo survey. The photometric sequence stars are labeled along with the SNe.

Fig. 2.— V band CCD images of the two SNe Ia, 1990O and 1992al, discovered at other observatories and included in the Calán/Tololo follow-up photometric program. The photometric sequence stars are labeled along with the SNe.

Fig. 3.— B, V, and I light curves for the 29 SNe Ia. In all cases the solid lines correspond to the best-fitting template. The next-best fit is also shown as dashed lines when the difference in the reduced χ^2 between the two best fits was $\leq$1.5.

Fig. 4.— Histogram showing the time with respect to B_{MAX} of the first photometric observation in B, V, or I. Note that for nearly one third of the SNe the photometric monitoring started before or at maximum light.